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Title:	Diamond diagnostics for synchrotrons, free-electron lasers and proton beams
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Diamond diagnostics for synchrotrons, free-electron lasers and proton beams

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Los Alamos National Laboratory

Sydor Seminar
September 1, 2021

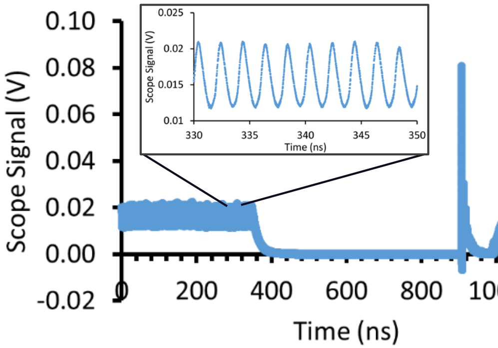
Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

LA-UR-20-28329

Diamond-based Detectors Grew Up at Synchrotrons

Diamond Properties:

- Low X-ray Absorption
- High Thermal Conductivity
- Mechanical Strength
- Radiation Hardness
- Indirect bandgap (no radiative recombination)
- Full charge collection at modest bias (0.1 V/μm)
- Fast - carrier mobility 4500/3800 $cm^2V^{-1}s^{-1}$ (e/h)

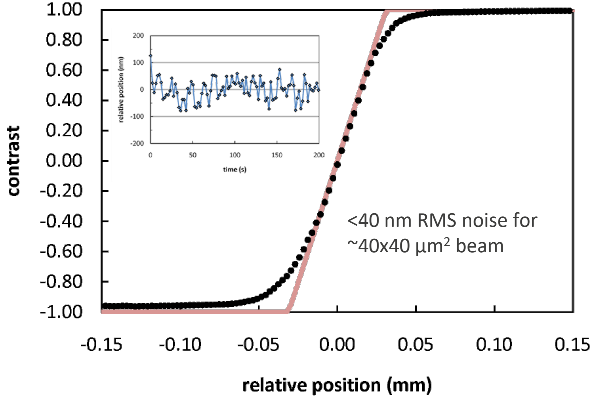


Fast (ns) timing

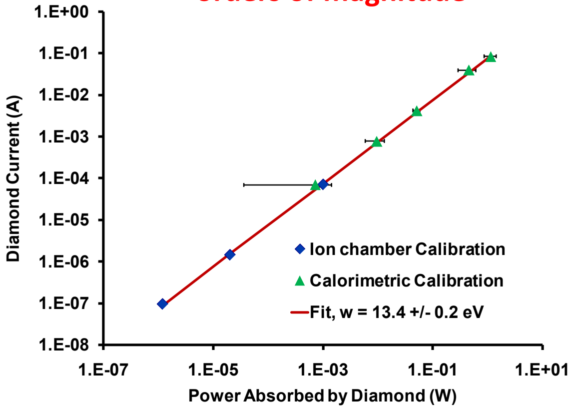
Commercialization of early devices (Sydor Technologies), ongoing SBIR efforts

Position sensitivity

RMS position noise of 0.1% of beam size

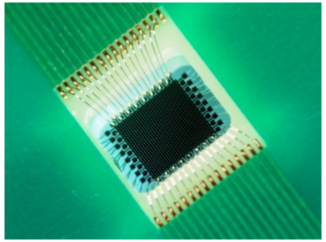


Flux linearity over more than 11 orders of magnitude

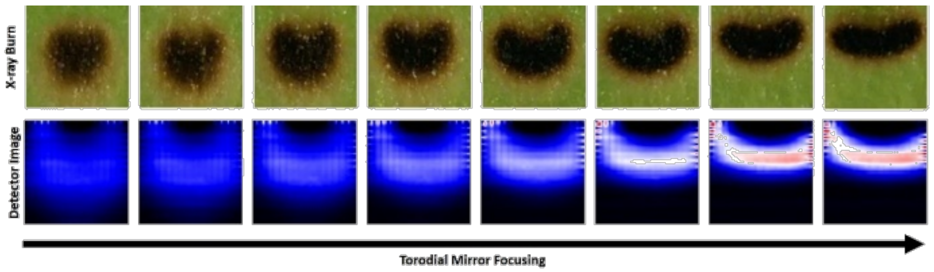


Bohon, Muller & Smedley (2010) JSR 17: 711

Beam Imaging



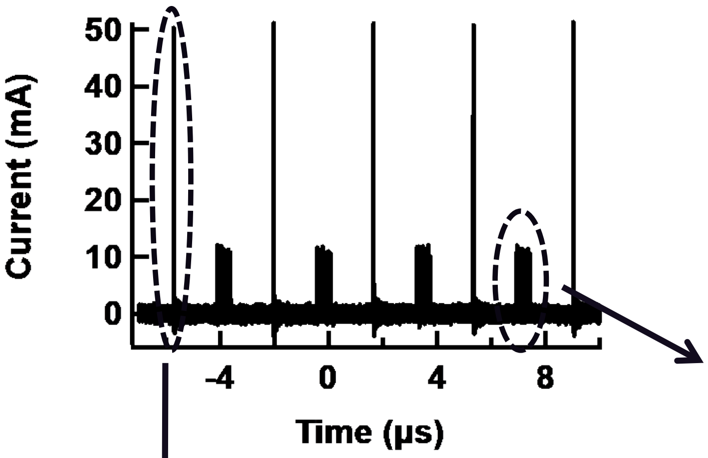
1k pixel Transparent X-ray Camera

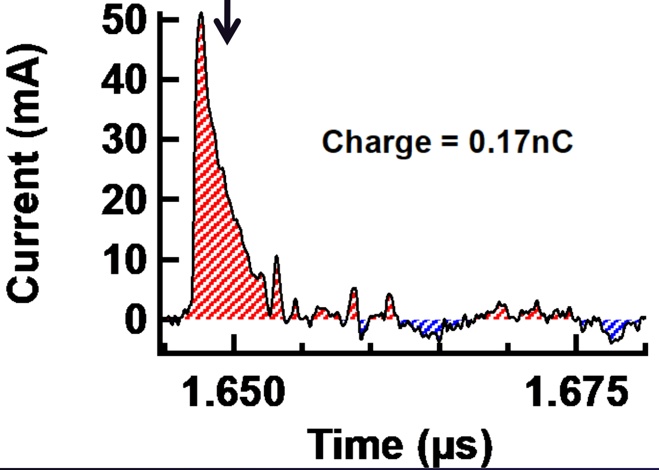


Zhou et al. (2015) JSR 22 :1396 (cover article)

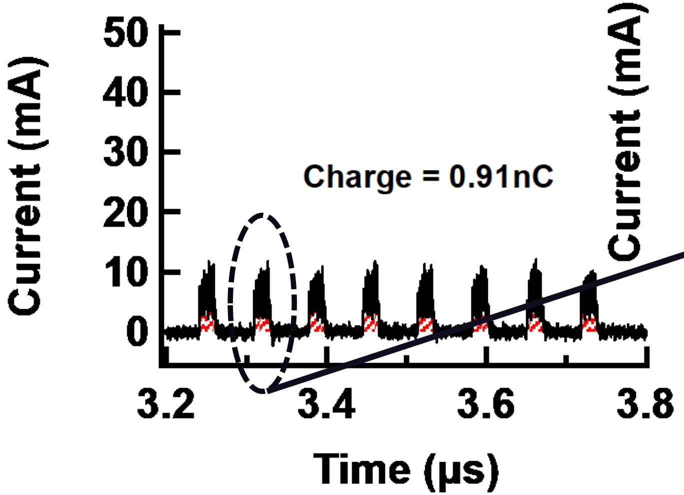
R&D100 2016 Finalist

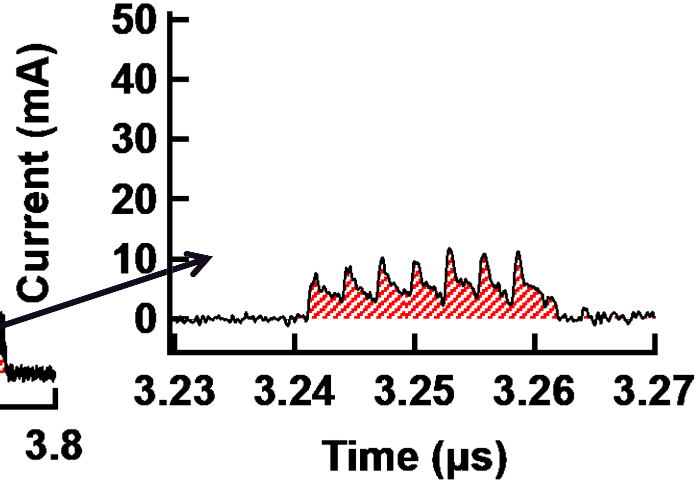
Diamond can resolve individual ring pulses linearly





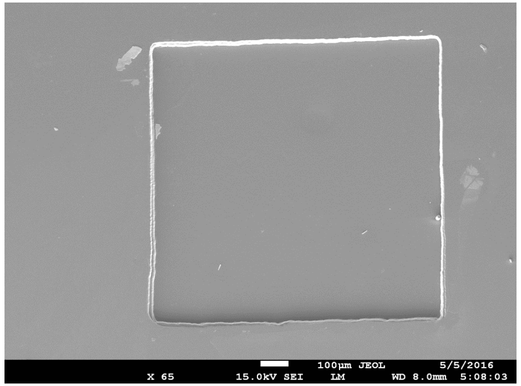
- Ring mode "hybrid fill, top up", APD ID11-D
- 102mA total, 16mA in first bunch, 86mA in remaining pulse train.
- Separated by 1.594 µs
- **Ratio of ring currents matches very closely to measured charge ratio**
- ***Current Ratio: 86mA/16mA = 5.38***
- ***Measured Q Ratio: 0.91nC/0.17nC = 5.35***

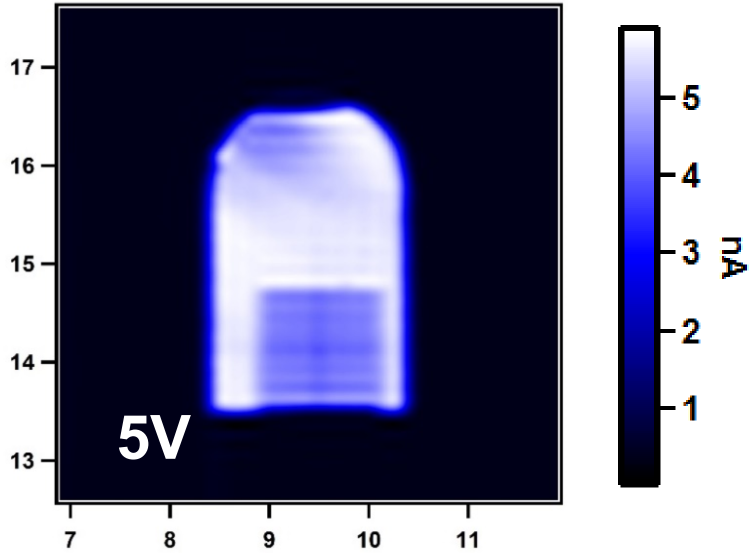


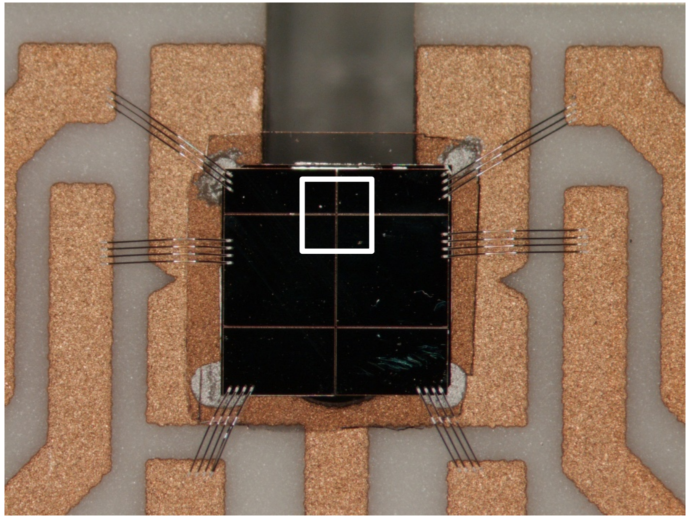


Diagnostics for a wide range of photon energies

- RIE ultrathin layers
  - 4 µm membranes
  - Transmits 2 keV photons
  - Potentially much faster response
  - 4 devices in use at SMI

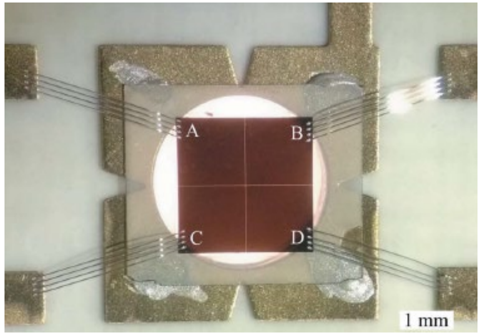


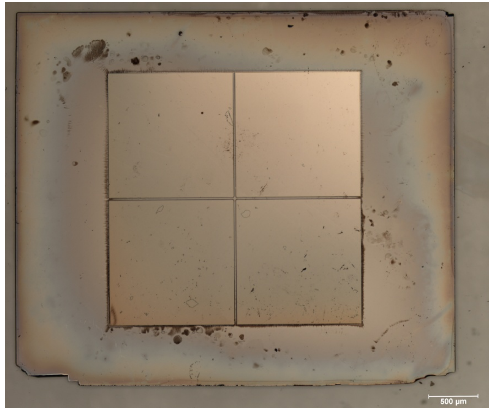


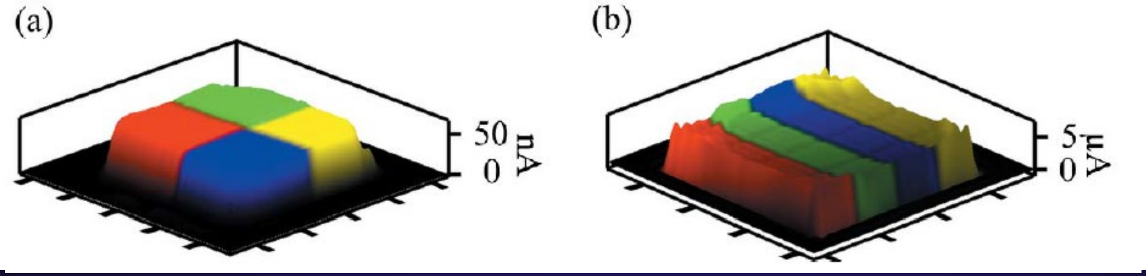


All diamond detectors with patterned UNCD electrodes

- Diamond Contacts – no longer the weakest link
- UNCD Grown at ANL,Lithographically masked RIE
- No fluorescent lines



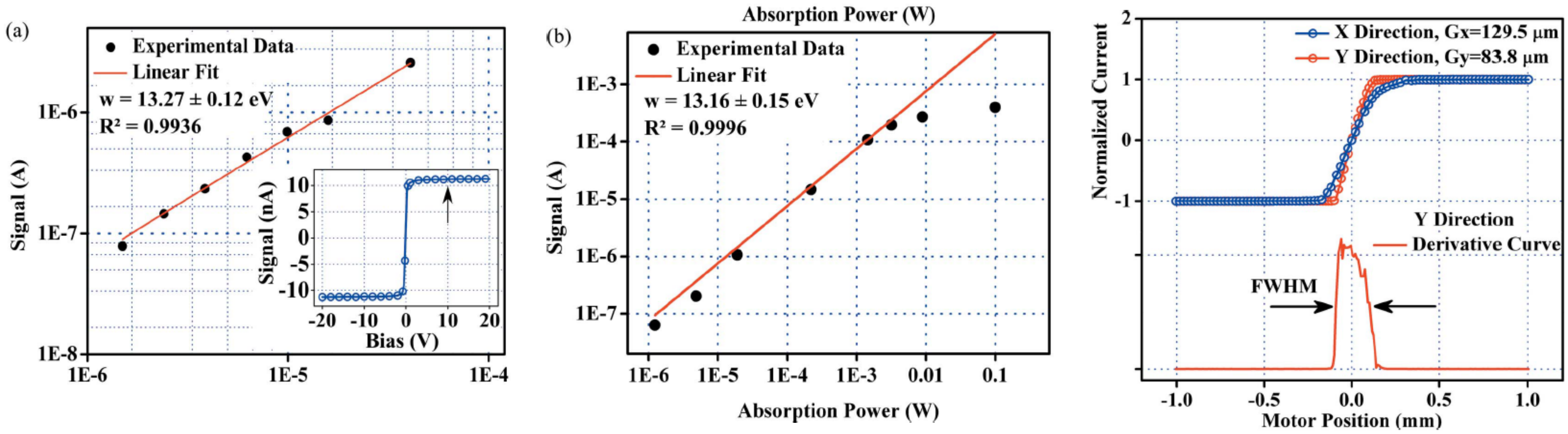




UNCD works best for low currents

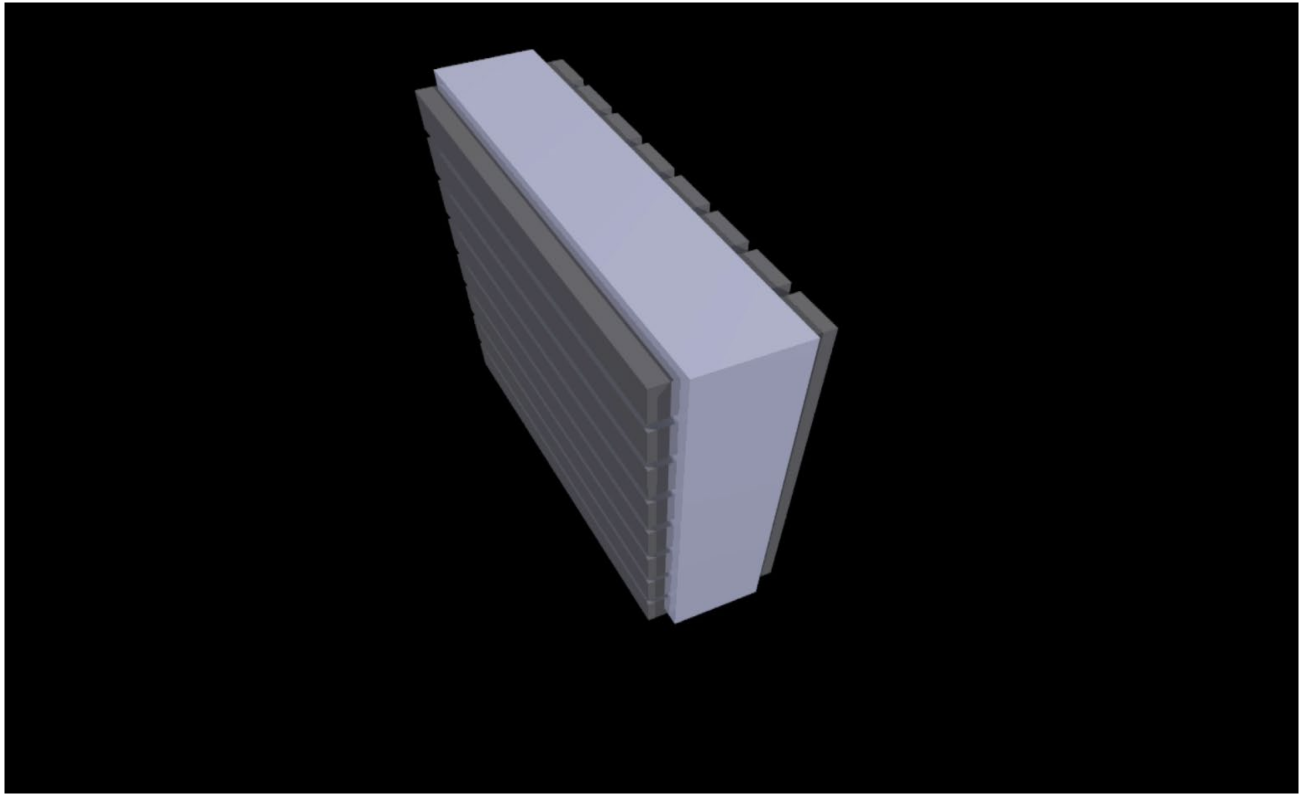
Conduction comes from sp-2 content (along grain boundaries)

Flux linearity limited at very high flux (>10^{13}) due to lower contact conductivity



J. Synchrotron Rad. (2018). 25, 1060–1067

Transparent x-ray beam imager



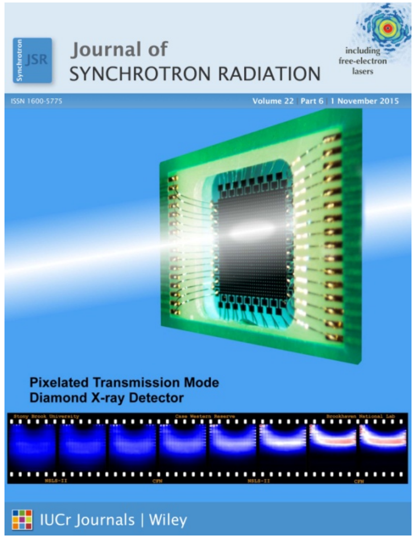
readout animation

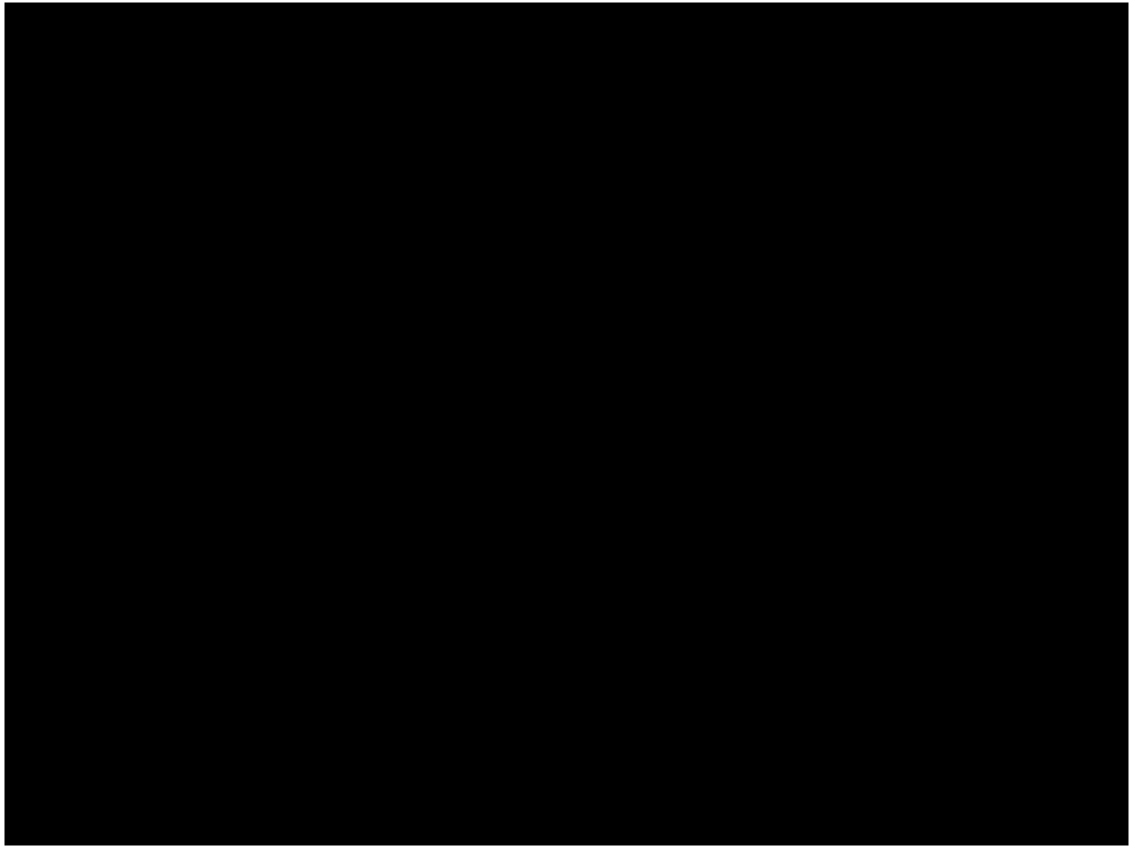
Image Readout

- 32 x 32 stripes, yielding 1024 pixels
- Only one row is active at a time minimizing ohmic heat generation.
- Project goal of real time imaging at 1 Hz, achieved 32 Hz
- Up to ~10mA per pixel

Pixels are created by metalizing one side of the diamond with horizontal stripes and the other with vertical stripes. As the x-rays pass through the diamond, the induced current is collected in each vertical stripe, while the bias is applied to individual stripes on the other side. This bias is cycled, allowing readout of one line of “pixels” at a time.

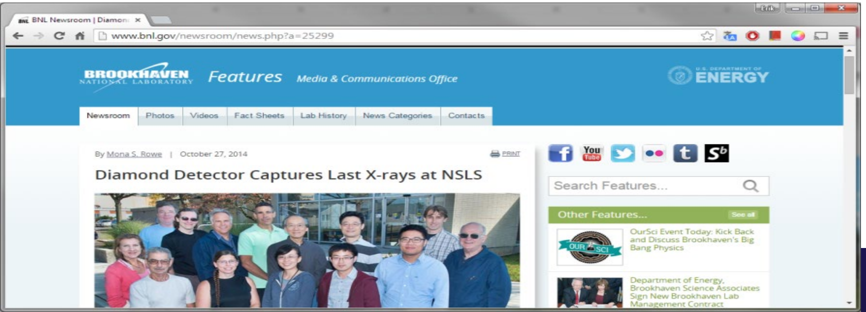
Transparent x-ray beam imager





R&D100 2016 Finalist

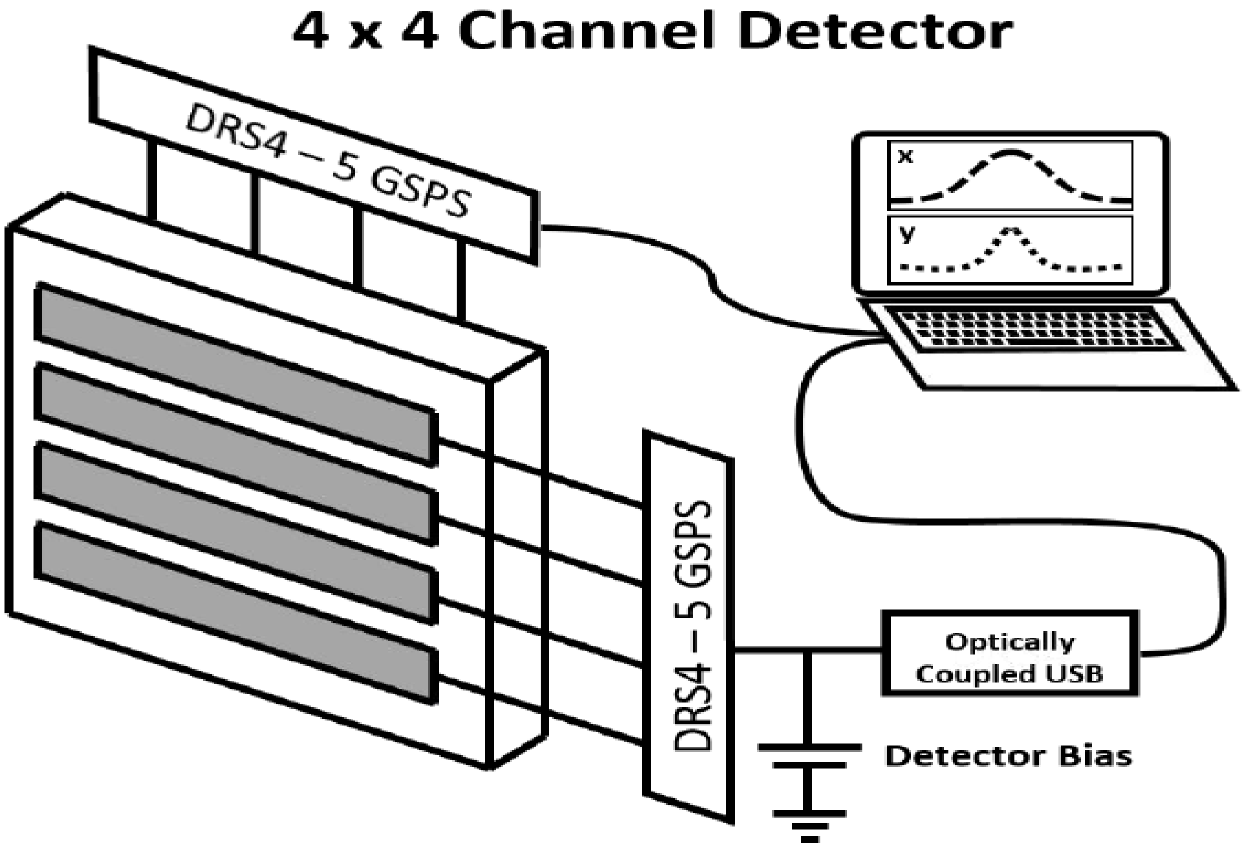
http://www.bnl.gov/newsroom/news.php?a=25299



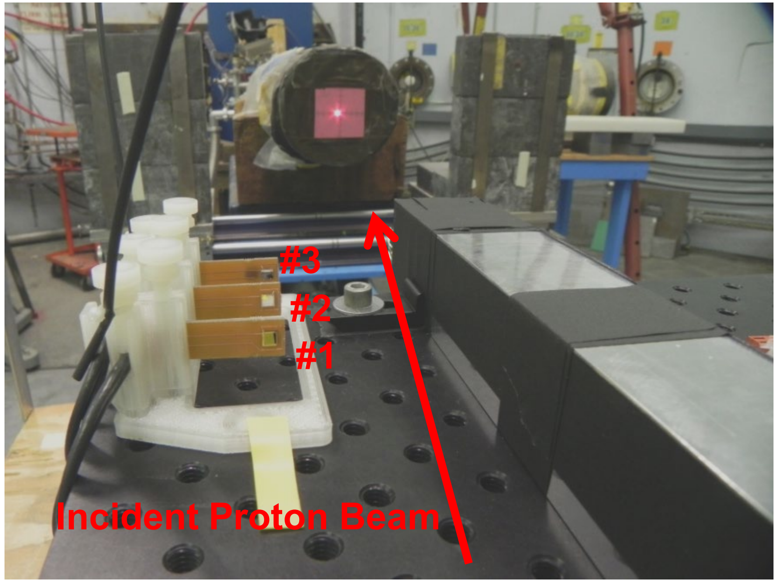
Zhou et al. (2015) JSR 22 :1396 (cover article)

Application to FELs and proton linacs

- Can not rely on pulse to pulse stability
- Can get shot by shot line out by measuring current on all detector channels
- Intend to redesign electronics to allow FPGA to measure current and/or bias strips independently
- Can also be configured as a variable-center quad, expanding the spatial dynamic range of the device for small beams



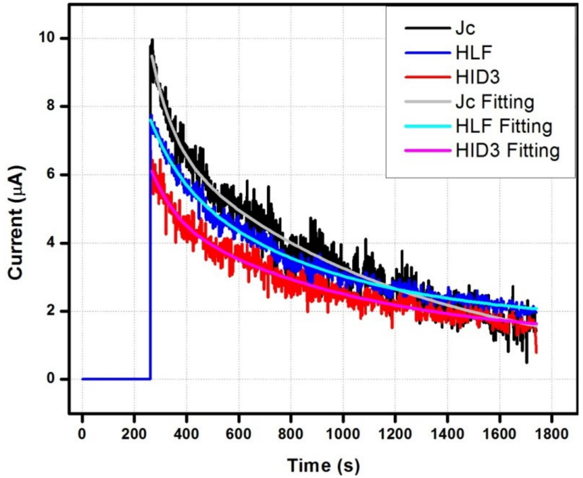
Proton Radiation Experiment



LANL blue room setup

- Proton Energy: 800 MeV
- Beam Flux: 10^{11} proton/(cm^2·s)
- Beam Size: diameter ~ 2.5 cm
- Exposure Time: 2180 seconds
- Incident Energy: 4.486 kJ
- Electrical Field: +0.1 V/µm

Real-time IBIC Monitoring @0.1 V/µm

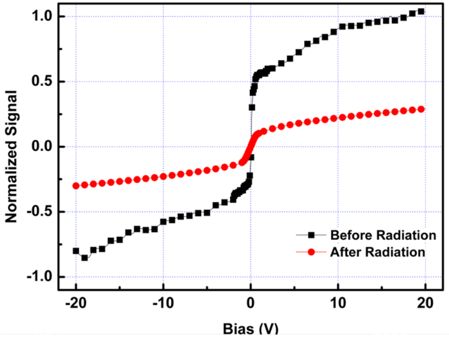


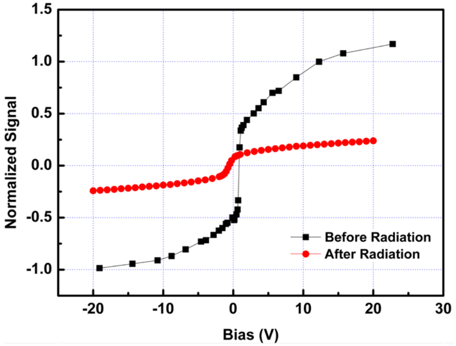
	Start Signal (µA)	End Signal (µA)	Signal Ratio	Lifetime (proton/cm^2)
Sample #1	7.425	2.088	**28.1%**	**4.62×10^{13}**
Sample #2	6.019	1.644	**27.3%**	**4.99×10^{13}**
Sample #3	9.805	1.640	**16.7%**	**5.47×10^{13}**

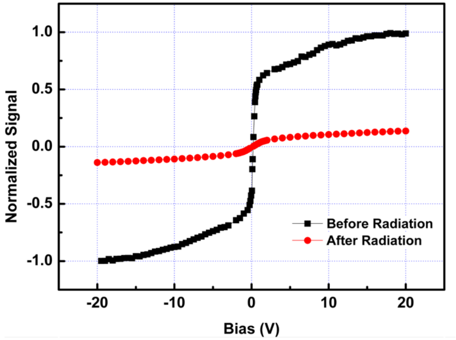
Electrical Performance Change

Sample #1 | Sample #2 | Sample #3

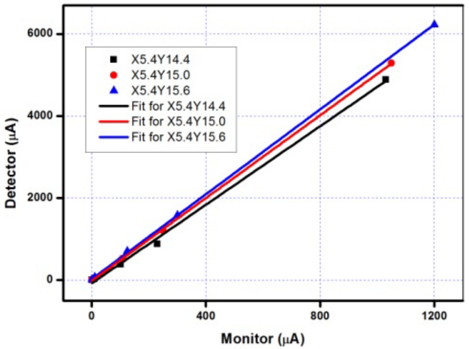
Before Radiation
vs
After Radiation

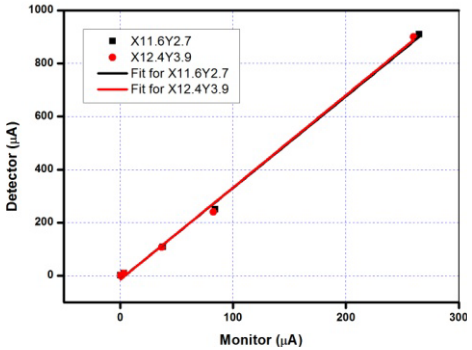


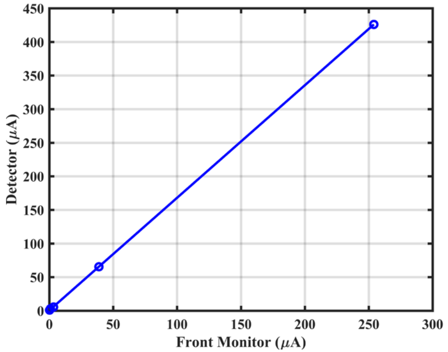




Flux Calibration
(@0.8 V/μm)

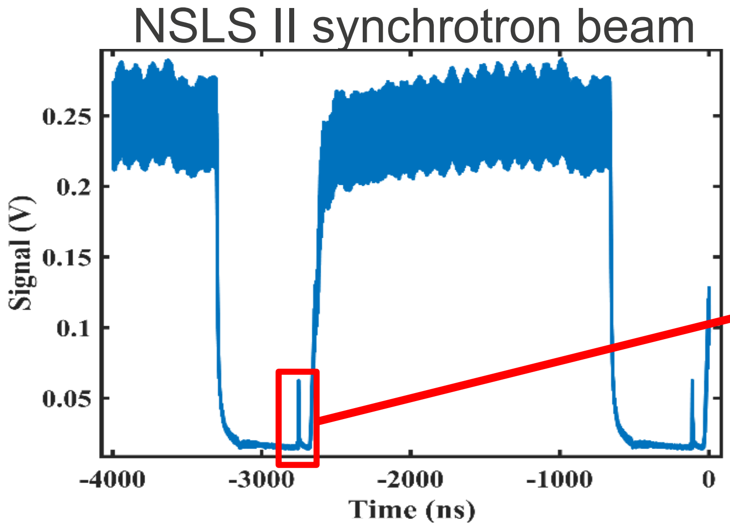


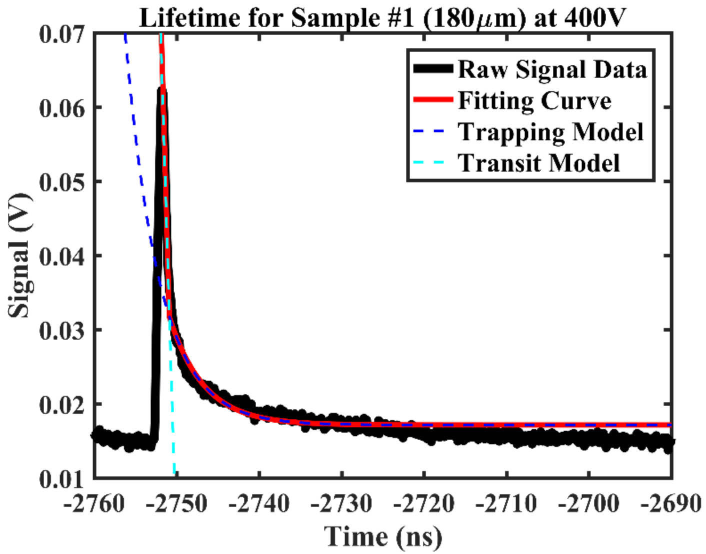




The diamond detector after proton radiation is still applicable as flux monitor
AIP Advances, 10 (2). Art. No. 025004 (2020)

Radiation Damage effect on Temporal Response





After 10^{14} protons (100 years of therapeutic dose), detector bulk response ~30% of initial

Carrier property (at 400V):

Transit time: ~ 0.67 ns

→ carrier velocity ~1209 $cm^2/(V \cdot s)$

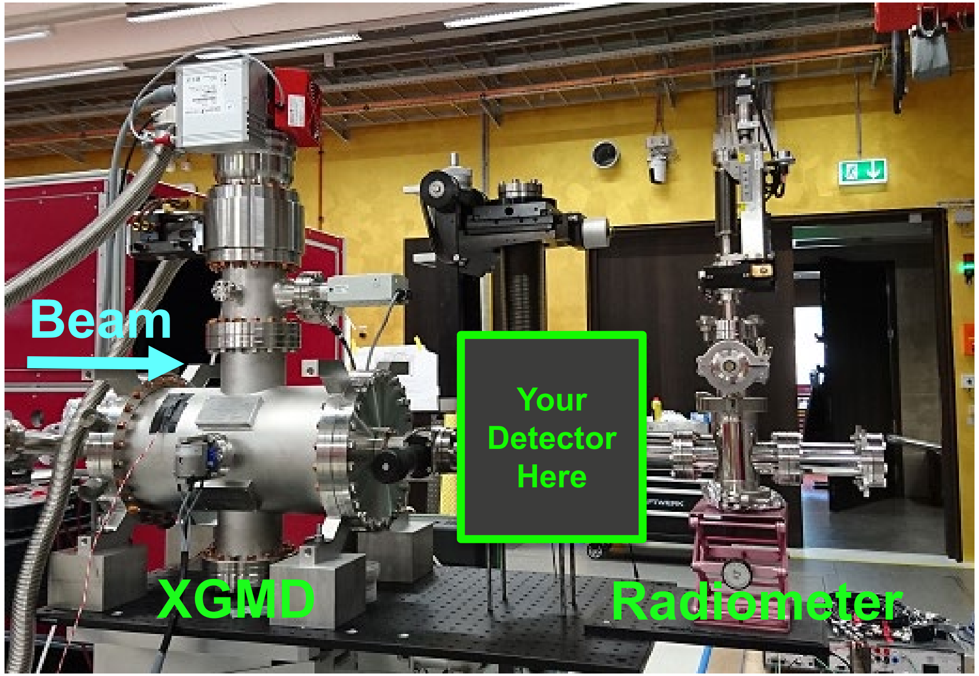
Trapping time: ~ 4.18 ns

=> Charge collection is significantly delayed by radiation damage

The Challenge was Set for Measuring XFEL Beams

- **PhotonDiag2018: the challenge and opportunity**

- Quickly formed an international collaboration
- 1 month until beamtime for Bernina commissioning experiment
- DESY XGMD and AIST Radiometer already lined up, but there is space between…
- Can we design and fabricate a device to perform pulse-by-pulse measurements of the XFEL beam at SwissFEL?



Proposed Experiment at SwissFEL Aramis Bernina

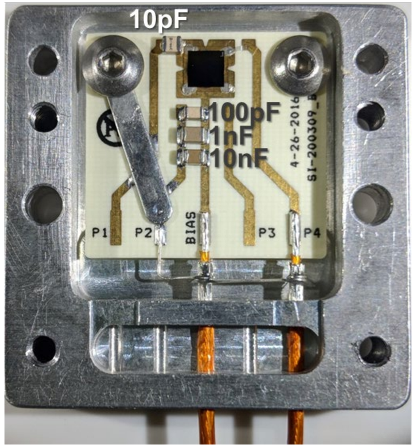
Challenge Accepted!

- **Designed and fabricated several devices in a highly collaborative effort:**

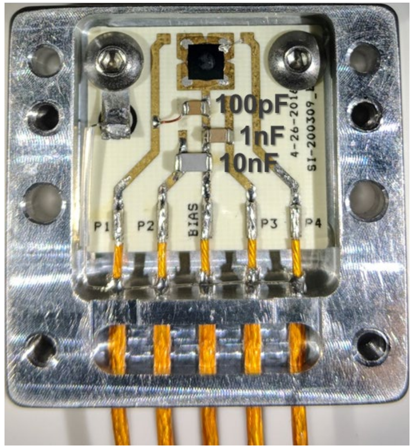
- UNCD contacts to avoid potential contact ablation (CNM, ANL)
- One detector with only UNCD contacts, one with an Al overlayer for better conductance (BNL, SBU)
- Adapted circuit boards and cases from our industry partners (Sydor Technologies)
- Added capacitance close to the sensor for rapid charge resupply (BNL)
- Used in-vacuum components and a hastily converted vacuum system… brought to SwissFEL in our *luggage*…

Devices Tested

Detector 1



Detector 2



Diamond Substrates: Element 6 electronic grade single crystal, 4 mm x 4 mm; active area 3 mm diameter from aperture in case

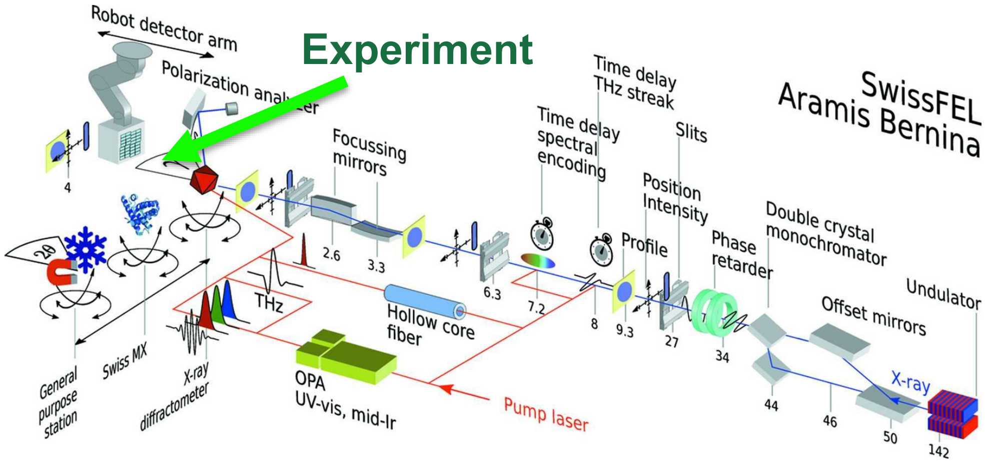
Diamond Thickness: 40 µm
UNCD: 400 nm

Diamond Thickness: 20 µm
UNCD: 500 nm
Al: 15 nm

Measurements at SwissFEL

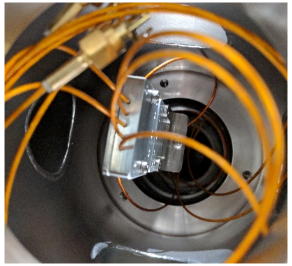
- **Transmission Measurement at the Bernina branch of the Aramis Beamline**

Juranic et al 2019, JSR 26: 2081

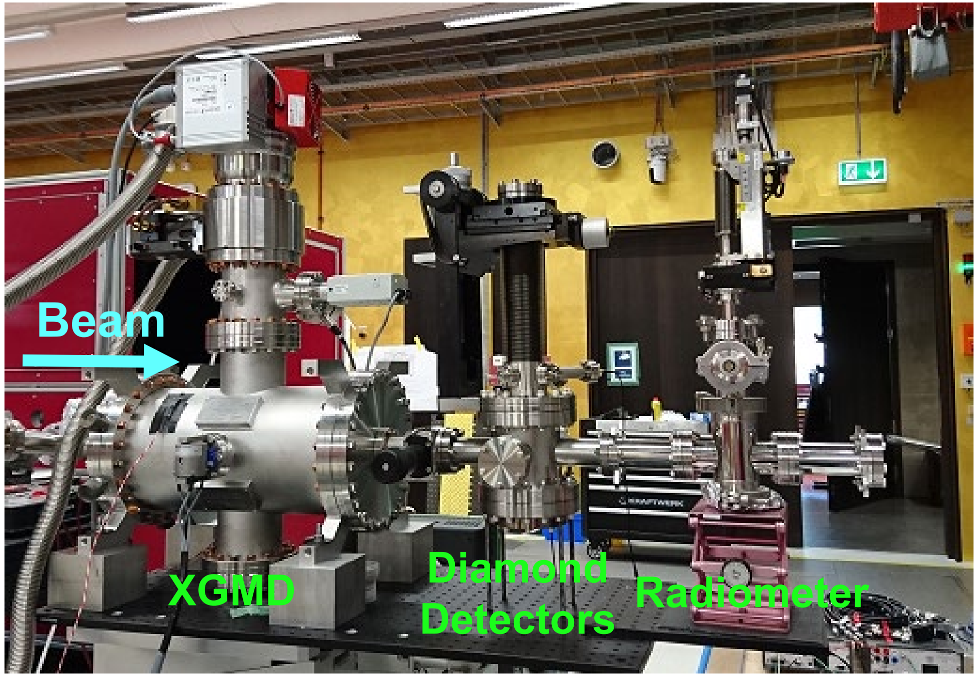


Schematic of the Bernina Branch of the Aramis Beamline

Ingold et al 2019, JSR 26: 874



Detectors (2) mounted in vacuum on manual x-y stage for alignment/retraction



Setup at SwissFEL Aramis Bernina

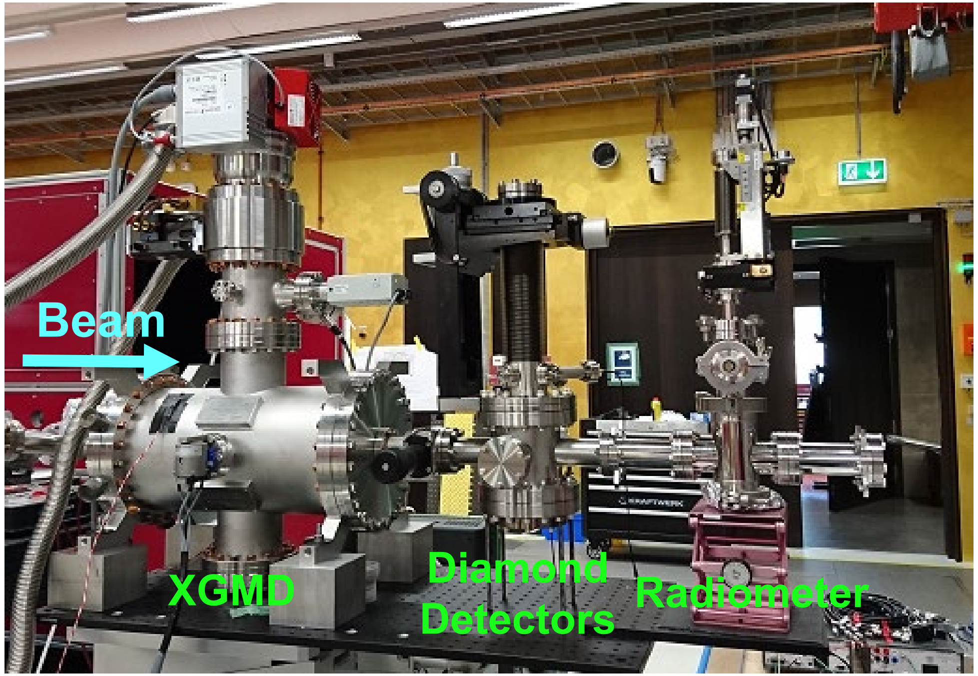
Measurements at SwissFEL

- **Transmission Measurement at the Bernina branch of the Aramis Beamline**

Juranic et al 2019, JSR 26: 2081

- Experimental Conditions:
  - **Photon Energy: 6080 eV, pink beam mode**
  - **Beam Flux: 10^{11} ph/pulse**
  - **Incident Energy: 200 uJ/pulse, 25 Hz**
  - **Electrical Field: Detector 1: -1.5 V/µm, Detector 2: +2 V/µm**

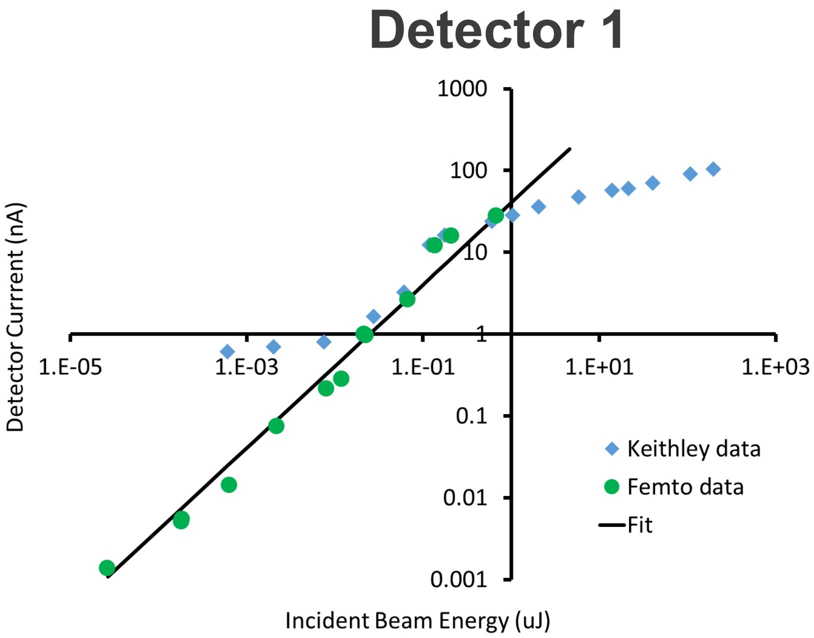
- Measurements:
  - Calibration of attenuators
  - Measurement of beamline transmittance
  - Linearity limits of the diamond devices:
    - Current Mode
    - Pulse-by-pulse Mode

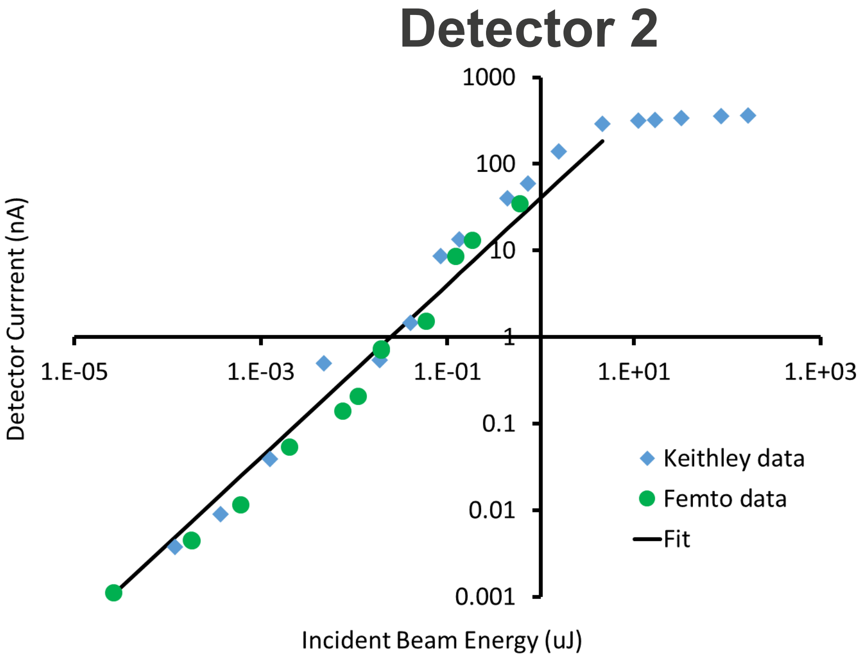


Setup at SwissFEL Aramis Bernina

Linearity Limits in Current Mode

- **Linearity in current mode was demonstrated over 5+ orders of magnitude in FEL beam, but saturation effects are evident at higher pulse energies**



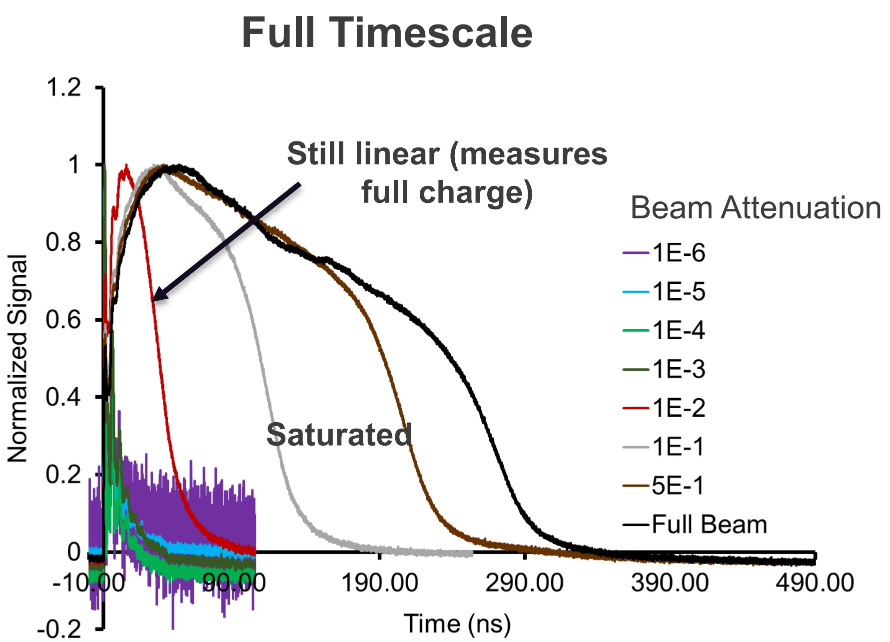


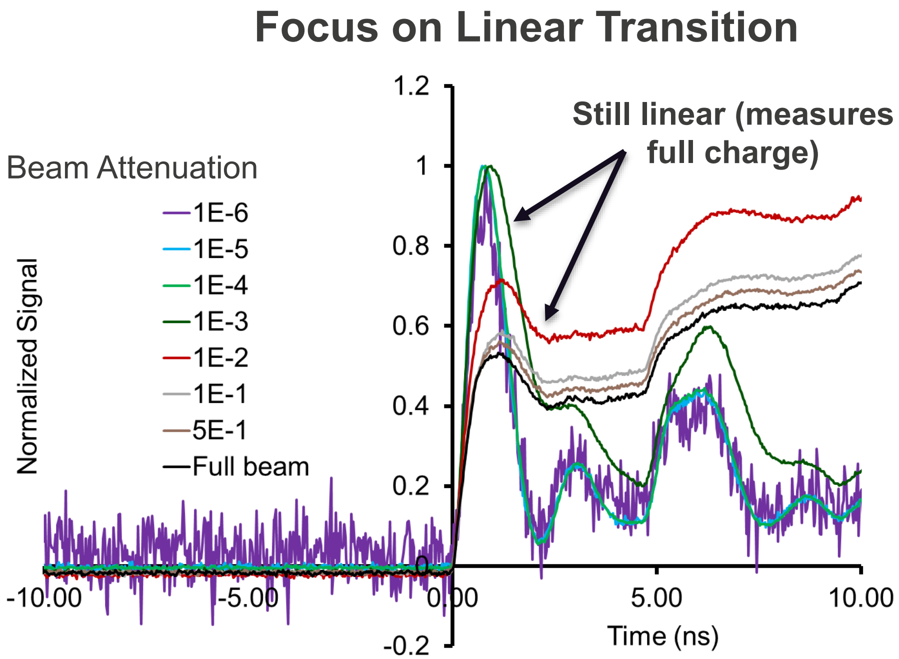
Response linear to ~0.3% of full beam

Response linear to ~3% of full beam

Linearity Limits in Pulse-by-pulse Mode

- **Pulse mode measurements reveal an interesting effect: pulse broadening occurs prior to loss of linearity**





Detector 2: Attenuation Series Shot-by-shot (fast oscilloscope)

Linearity Limits in Pulse-by-pulse Mode

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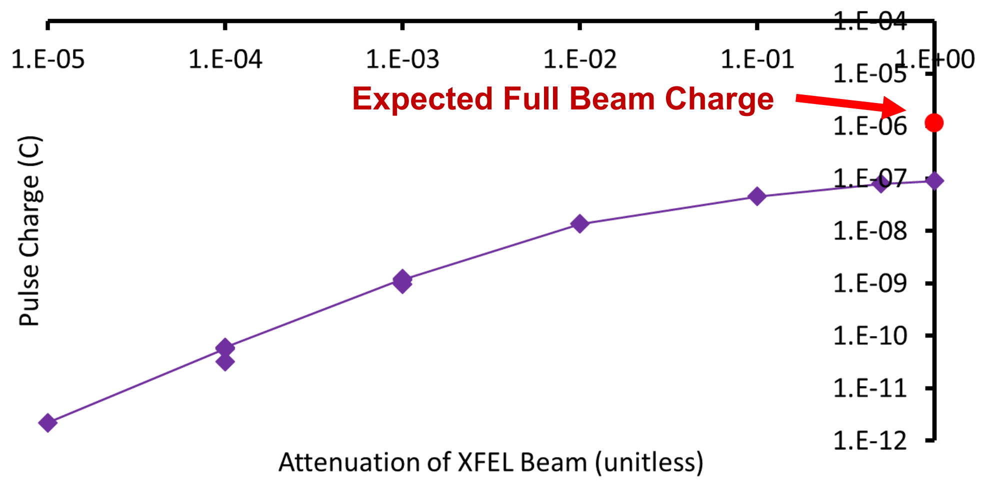
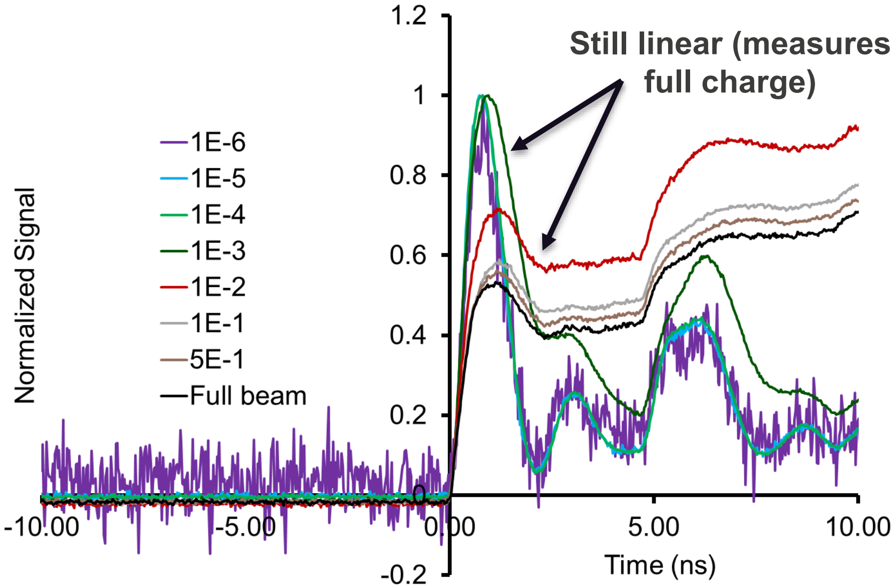
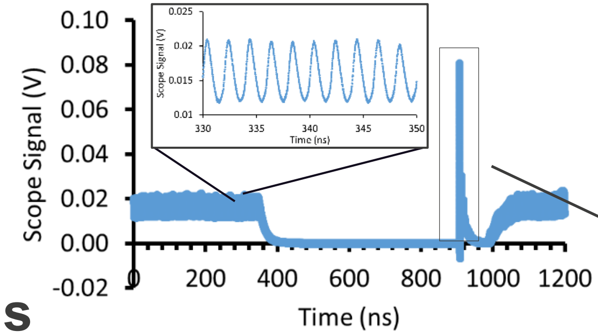




Detector 2: Attenuation Series Shot-by-shot (fast oscilloscope)

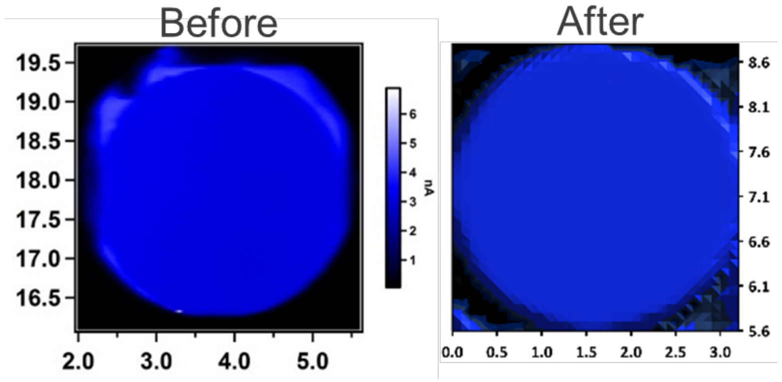
Post-analysis at NSLS-II

- **Measurements at NSLS-II: damage analysis and pulse shape study**

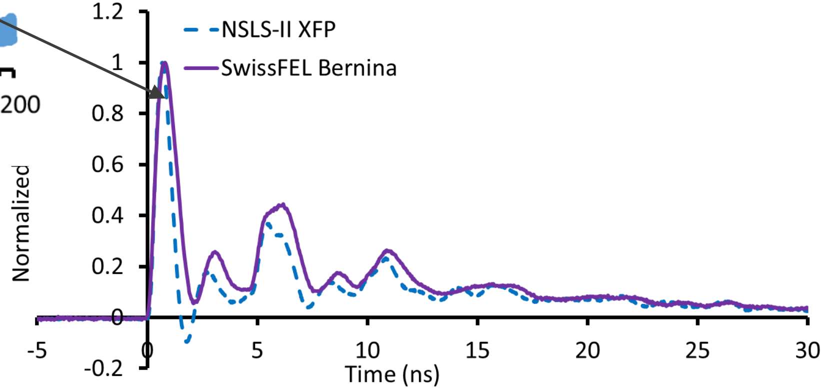


Damage Analysis

- Detector response (XBIC) is unchanged due to use in XFEL beam



Pulse shape study



Pulse shape similarity SwissFEL vs. NSLS-II; shape is a function of cabling and PCB design

- Both show the same pulse shape – shape due to board design and not a property of measuring the XFEL

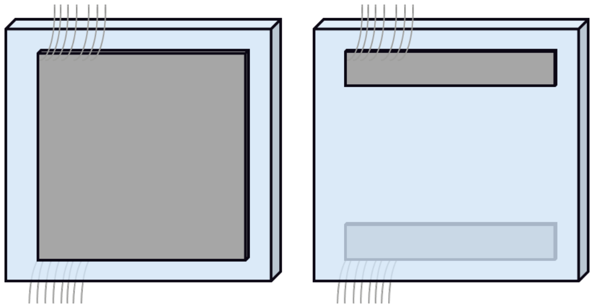
What is Limiting the Linearity of the Response?

Identified 3 potential issues:

- Space charge in the material (physical limitation of the material)
  - Where this occurs is what we would eventually like to determine
- Capacitance: not enough or too distant (otherwise known as "your power supply is infinitely far away")
  - We thought we addressed this with on-board capacitors, but it may not have been enough
- Back EMF/Inductance
  - Could kill the bias or worse (could see large bias spikes with short pulses – meaning that the *best case* scenario is deviation from linearity…)

How Do We Improve the Design?

- **Mitigation strategies:**
  - Contact geometry
    - perpendicular charge movement (also allows use of less resistive contacts)



  - Add capacitance to the circuit
  - Reduce inductance and/or stretch the pulse in time
    - Avoid wire bonds and add parallel capacitors
    - For fully absorbing spectra, this could mean using thicker diamonds

Acknowledgements

Takahiro Tanaka[2], S Owada[2], Anirudha Sumant[3], John Smedley[1], Markus Degenhardt[4], Ulf Jastrow[4], Andrey Sorokin[4], Kai I. Tiedtke[4], Pavle Juranic[5], Erik M. Muller[6,7], Mengnan Zou[6]

[1] Los Alamos National Laboratory, NM, USA

[2]AIST, Tsukuba, Ibaraki, Japan

[3]Argonne National Laboratory, IL, USA

[4]DESY, Hamburg, Germany

[5]Paul Scherrer Institute, Villigen, Switzerland

[6]State University of New York at Stony Brook, NY, USA

[7]Brookhaven National Laboratory, NY, USA

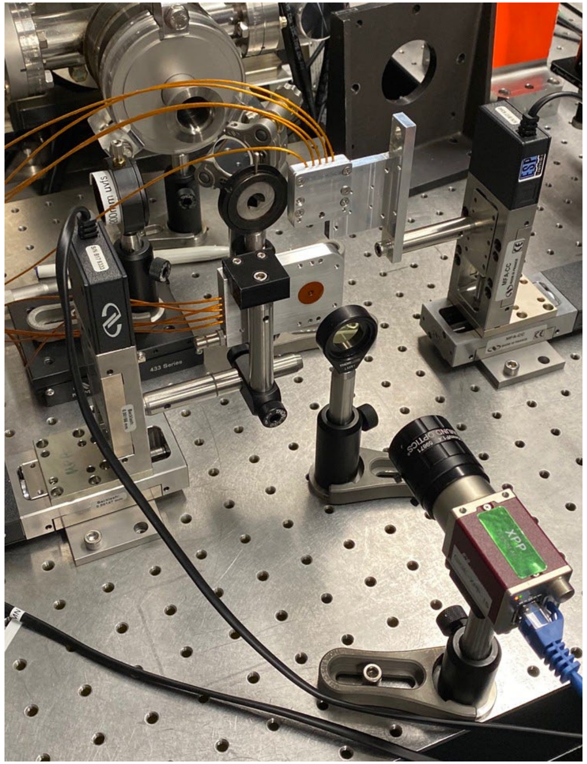
University of California (UC) Laboratory Fees Collaborative Research Program (new 3 year multi-institution funded program):

Advanced Detectors for XFELs and Proton Accelerators

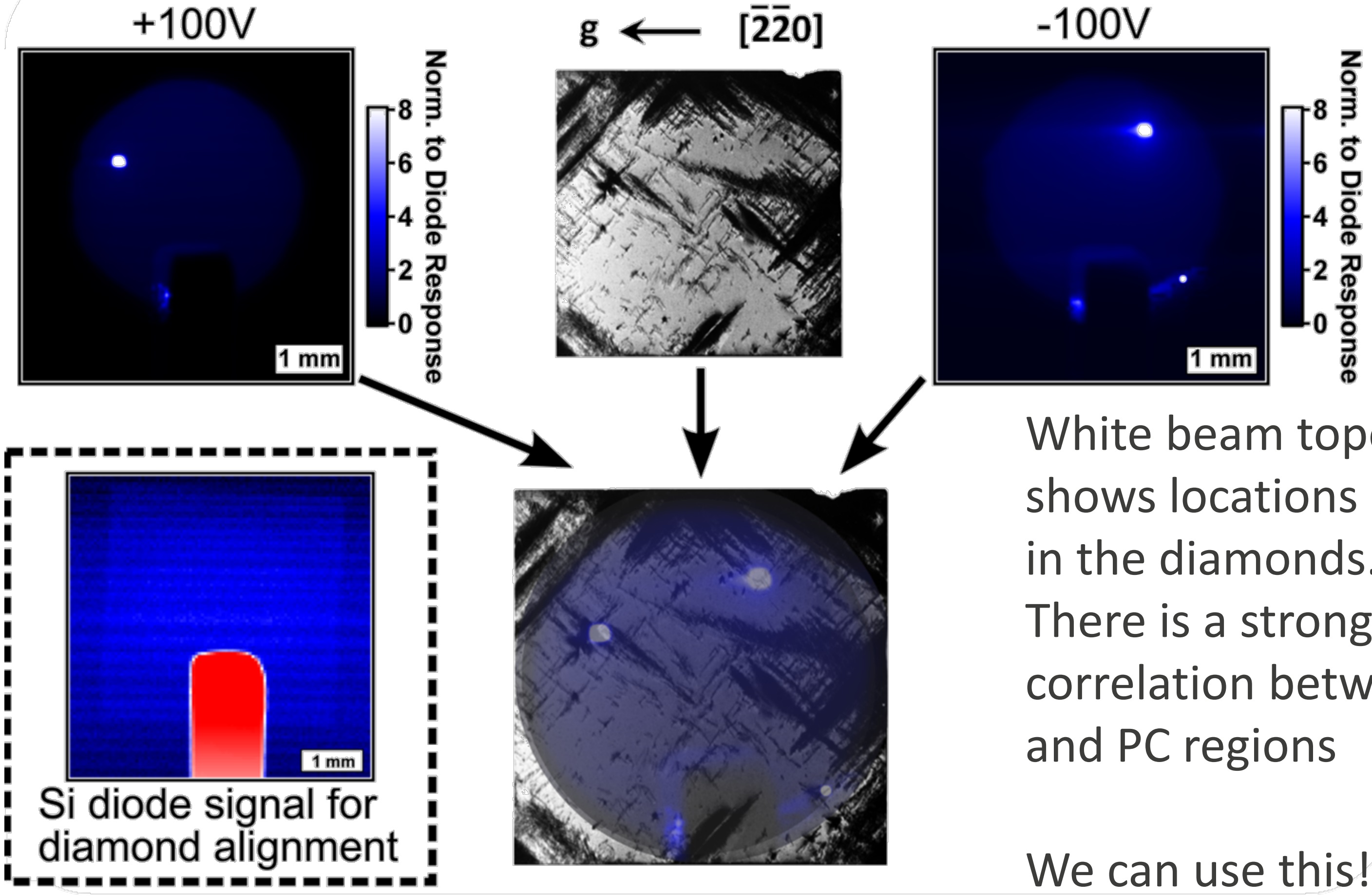
UC Davis
Los Alamos National Lab
UC Santa Cruz
UC Santa Barbara
Lawrence Berkeley National Lab

LCLS Experiment (Hot off the Presses!)

- **Measurement October 14 2020**
- **LCLS, XPP beamline**
- **9900 eV beam, 30 uJ maximum pulse energy**
- **Comparison of Detector 2 with standard diamond detector (Pt contacts, no additional capacitance); measured simultaneously**
- **Pulse-by-pulse linearity scans**
  - as a function of applied bias
  - as a function of discrete beam sizes (over 3 orders of magnitude)
- **Data coming soon!**
- **Next Beamtime: Nov 2020 to test new board**



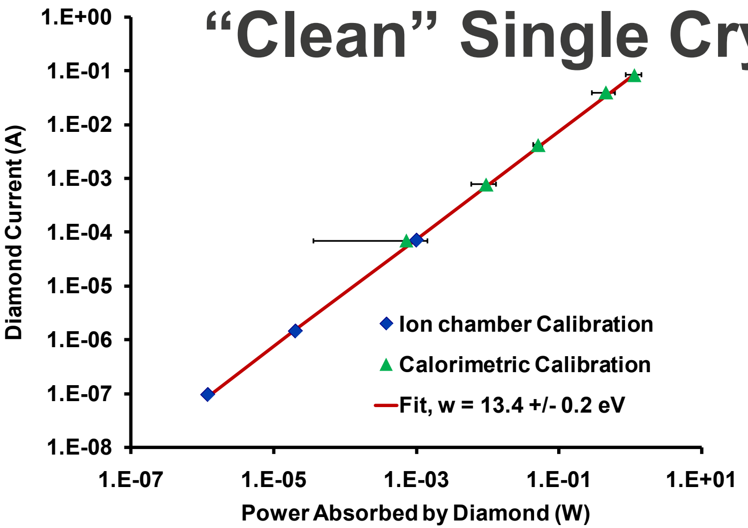
Photoconductive gain caused by localized charge trapping

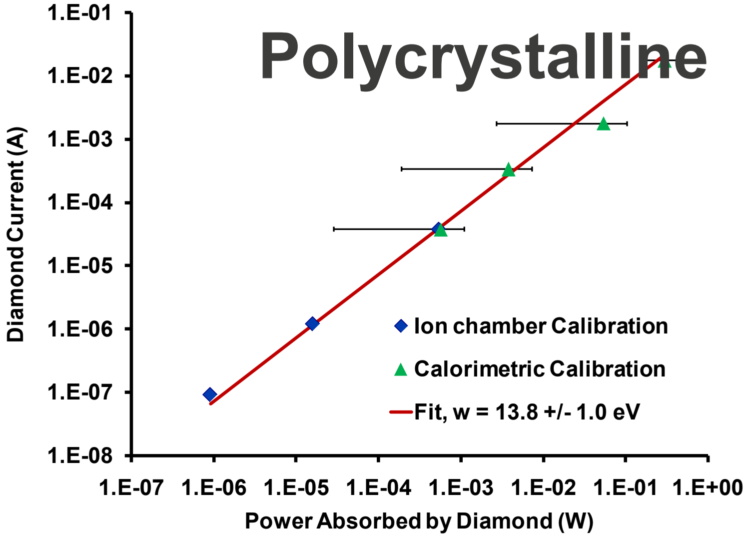


White beam topography shows locations of dislocations in the diamonds.
There is a strong spatial correlation between dislocations and PC regions

We can use this!

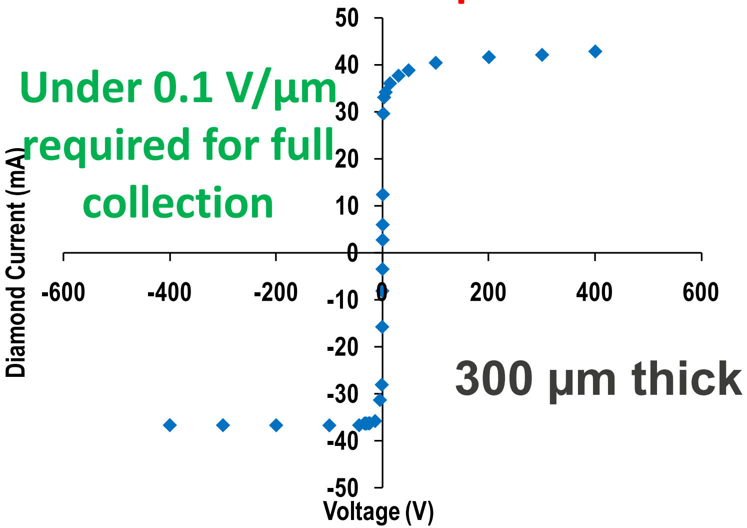
Response vs Flux and Bias



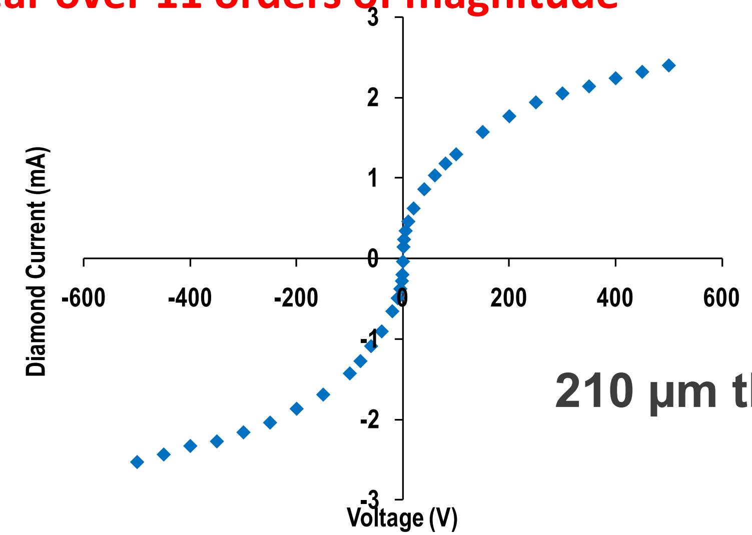


Response to incident flux linear over 11 orders of magnitude

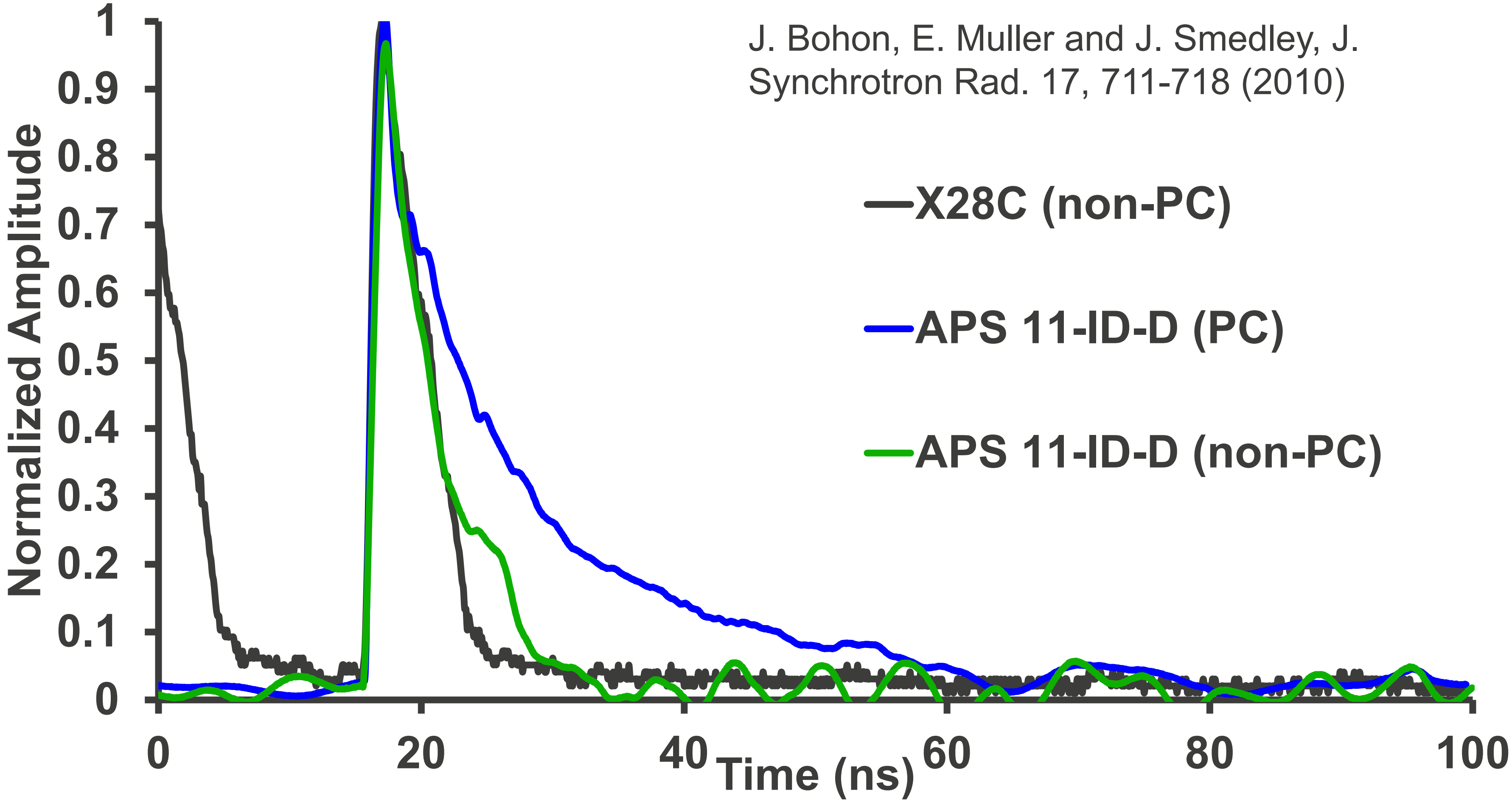
Under 0.1 V/µm required for full collection



300 µm thick plate



210 µm thick plate


J. Bohon, E. Muller and J. Smedley, J. Synchrotron Rad. 17, 711-718 (2010)
X28C (non-PC)
APS 11-ID-D (PC)
APS 11-ID-D (non-PC)
Normalized Amplitude
Time (ns)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100